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Assessment of blood lead level declines in an area of historical mining with a holistic remediation and abatement program

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ABSTRACT

Lead exposure and blood lead levels (BLLs) in the United States have declined dramatically since the 1970s as many widespread lead uses have been discontinued. Large scale mining and mineral processing represents an additional localized source of potential lead exposure in many historical mining communities, such as Butte, Montana. After 25 years of ongoing remediation efforts and a residential metals abatement program that includes blood lead monitoring of Butte children, examination of blood lead trends offers a unique opportunity to assess the effectiveness of Butte's lead source and exposure reduction measures. This study examined BLL trends in Butte children ages 1–5 ($n=$ 2796) from 2003–2010 as compared to a reference dataset matched for similar demographic characteristics over the same period. Blood lead differences across Butte during the same period are also examined. Findings are interpreted with respect to effectiveness of remediation and other factors potentially contributing to ongoing exposure concerns.

Reference population comparison: BLLs from Butte were compared with a reference dataset ($n=2937$) derived from the National Health and Nutrition Examination Survey. The reference dataset was initially matched for child age and sample dates. Additional demographic factors associated with higher BLLs were then evaluated. Weights were applied to make the reference dataset more consistent with the Butte dataset for the three factors that were most disparate (poverty-to-income ratio, house age, and race/ethnicity). A weighted linear mixed regression model showed Butte geometric mean BLLs were higher than reference BLLs for 2003–2004 (3.48 vs. 2.05 μg/dL), 2005-2006 (2.65 vs. 1.80 μg/dL), and 2007-2008 (2.2 vs. 1.72 μg/dL), but comparable for 2009–2010 (1.53 vs. 1.51 μg/dL). This trend suggests that, over time, the impact of other factors that may be associated with Butte BLLs has been reduced.

Comparison across Butte: Neighborhood differences were examined by dividing the Butte dataset into the older area called "Uptown", located at higher elevation atop historical mine workings, and "the Flats", at lower elevation and more recently developed. Significant declines in BLLs were observed over time in both areas, though Uptown had slightly higher BLLs than the Flats (2003–2004: 3.57 vs. 3.45 μg/dL, $p=0.7$; 2005–2006: 2.84 vs. 2.52 μg/dL, $p=0.1$; 2007–2008: 2.58 vs. 1.99 μg/dL, $p=0.001$; 2009–2010: 1.71 vs. 1.44 μg/dL, $p=0.02$). BLLs were higher when tested in summer/fall than in winter/spring for both neighborhoods, and statistically higher BLLs were found for children in Uptown living in properties built before 1940. Neighborhood differences and the persistence of a greater percentage of high BLLs (> 5 μg/dL) in Butte vs. the reference dataset support continuation of the home lead abatement program.

Conclusions: Butte BLL declines likely reflect the cumulative effectiveness of screening efforts, community-wide remediation, and the ongoing metals abatement program in Butte in addition to other factors not accounted for by this study. As evidenced in Butte, abatement programs that include home evaluations and assistance in addressing multiple sources of lead exposure can be an important complement to community-wide soil remediation activities.

1. Introduction

Over the past four decades, blood lead levels (BLLs) have declined dramatically as bans on leaded gasoline and lead in paint, plumbing, and solder for canned foods have spread around the world; however, higher BLLs persist among some individuals,

Abbreviations: BLLs, Blood Lead Levels; BSB, Butte-Silver Bow; CDC, Centers for Disease Control and Prevention; NHANES, National Health and Nutrition Examination Survey; PIR, Poverty-to-Income Ratio; WIC, Women, Infants, and Children

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including potentially those people who live in close proximity to some historical mining operations (Boreland et al., 2008; Kim et al., 2012; Lanphear et al., 2003; Park et al., 2014; Taylor et al., 2014; Zhang et al., 2012). Only rarely have remediation and abatement efforts been demonstrated to reduce BLLs in these communities (Boreland et al., 2008; Hilts et al., 1998; National Research Council, 2005; Sheldrake and Stifelman, 2003). Boreland et al. (2008) conclude that soil stabilization and storm water controls, along with home remediation and health promotion, were effective in reducing BLLs in the Broken Hill community in New South Wales, Australia between 1991 and 2007, and Sheldrake and Stifelman (2003) describe the effectiveness of a community-wide, preventative approach in a former smelter community in Idaho.

Butte, Montana was the center of copper mining in North America during the late 1800s and by the early twentieth century had more than 450 mines (U.S. Environmental Protection Agency, 2014). Mine waste dumps and overburden piles were interspersed with residential areas throughout the older parts of the community. The Butte Area site, with a boundary spanning from the Continental divide west along Silver Bow Creek to the Warm Springs Ponds, was placed on the United States (U.S.) Superfund National Priorities List in 1983. Cleanups of mine wastes in Butte occurred between 1988 and 2004 with a focus on stabilizing, capping, or removing hundreds of thousands of cubic yards of waste and contaminated soil from waste dumps and residential yards and installing sedimentation ponds to address stormwater runoff (U.S. Environmental Protection Agency, 2014). Most of the planned long-term cleanup and restoration activities have been completed, including redevelopment and reuse projects that resulted in public parks, activity centers, and extensive walking/biking trails for the community; however, residential lead abatements are still ongoing.

An exposure study performed in 1990 by the Butte-Silver Bow (BSB) Health Department and the University of Cincinnati identified statistically significant differences in children's BLLs across selected areas of Butte (Butte-Silver Bow Department of Health and University of Cincinnati, 1992). The overall geometric mean BLL for Butte children, 3.5 μg/dL, was not found to be elevated relative to typical BLLs at that time in the U.S.; however, no formal analysis comparing Butte BLLs with those of a comparable reference dataset was performed. The 1990 study included collocated measures of soil and house dust concentrations, measures of lead in tap water, lead paint assessments, and administration of a questionnaire on household lead sources and socioeconomic information. Children from older neighborhoods where soil concentrations were more likely to be affected by both mining and non-mining related lead sources had higher geometric mean BLLs (3.7–4.6 μg/dL) than children from more recently developed neighborhoods (2.3–3.0 μg/dL).

The 1990 study showed that residence location (i.e., neighborhood area) and house age were the strongest predictors of paint lead, soil lead, and dust lead concentrations in Butte. Lead-based paint was shown to be associated with lead contaminated soil, which in turn was associated with lead contaminated house dust. Only house dust lead was directly related to blood lead. The indirect effect of soil lead on blood lead was shown to be both small and weak: only 5.4 percent of variance in blood lead was found to be indirectly attributable to lead in soil. The investigators concluded that 39 percent of the variability in soil lead concentrations was attributable to lead-based paint, while the remainder (61 percent) was attributable to "the heterogeneous distribution of lead in soil, and lead from other sources such as native lead in soil, mine waste, and contaminates from ore processing". Gardening or eating home grown produce did not contribute to elevated BLLs.

Based on the 1990 study findings, the University of Cincinnati investigators recommended the development of a program in Butte to identify and address residential lead exposure from all sources. From this early program came the current, ongoing, multi-pathway residential metals abatement program, designed to mitigate harmful exposure to lead, arsenic, and mercury in the Butte Priority Soils Operable Unit and an adjacent area. This program works in conjunction with the BSB Health Department and the state's Women, Infants, and Children (WIC) program, which has provided free blood lead testing to thousands of children over the past decade. Any child with a high blood lead is referred to the residential metals abatement program (Butte-Silver Bow County, Atlantic Richfield Company, 2010). The program then performs a home evaluation to identify the source of lead, including sampling for indoor dust, outdoor soil, indoor and outdoor paint, and lead in drinking water (from plumbing). Based on a series of criteria, varying levels of abatement are then performed at the property. As of 2013, the program has sampled approximately 2340 of the 3646 properties (64 percent) included within the program's target area and performed abatement events at more than 500 properties. The soil lead cleanup of 1200 mg/kg was based on a risk assessment and bioavailability studies showing low relative bioavailability of lead in Butte soil (U.S. Environmental Protection Agency, 2006). In addition to environmental assessments and abatements, the county also offers community educational resources.

The objective of this study was to examine BLL trends in Butte children ages one through five from 2003 to 2010 as compared to a reference dataset matched for similar demographic characteristics over the same period. Children of this age range were the focus because they are a vulnerable population and are known to have higher BLLs than older children and adults (Bellinger, 2004). Because the 1990 lead exposure study found significant differences in BLLs across Butte neighborhoods, this study also examined child blood lead differences across Butte neighborhoods from 2003 to 2010. Results of both analyses are interpreted with respect to effectiveness of remediation and other factors potentially contributing to ongoing exposure concerns.

A variety of demographic and socioeconomic factors are known to correlate with BLLs in children. Development of a reference dataset requires consideration of the relative importance of these factors, as well as the variation in these factors between the target and reference datasets. Major factors associated with higher BLLs include child age, race/ethnicity, socioeconomic status, and house age (Centers for Disease Control, 2013a, 2000; Gee and Payne-Sturges, 2004; Jones et al., 2009; Levin et al., 2008; Sargent et al., 1995). Higher BLLs in 2-3 year old children are thought to be associated with greater hand-to-mouth activity and other behaviors associated with this age range (ACCLP, 2012; Gaitens et al., 2009). The reasons why BLLs vary with race/ethnicity and socioeconomic status are less clear. Older house age is also associated with higher geometric mean BLLs (Alder et al., 1993; Kim et al., 2002). The prevalence of lead-based paint in U.S. housing is higher in housing built before 1940 than in housing built in subsequent decades, leading up to the ban of lead-based paint in such housing in 1978 (U.S. Consumer Product Safety Comission, 1977; U.S. Department of Housing and Urban Development, 2001). Older houses are more likely to have higher lead-based paint concentrations and deteriorated paint surfaces that increase exposure potential. Plumbing with lead pipes or solder or lead-containing fittings is also more likely to be present in older homes; lead was banned from plumbing in 1986 (U.S. Environmental Protection Agency, 1989). Many other lead sources have also been associated with higher BLLs, including crystal glassware and ceramic dishes, chocolate and imported foods and spices, traditional medicines, old vinyl mini-blinds and other vinyl products, a broad range of children's products and toys, and hobbies using lead solder (e.g., making stained glass or lead to cast bullets or lead sinkers for fishing) (Beaucham et al., 2014; Gulson et al., 2009; Levin et al., 2008).

2. Methods

This cross-sectional study examines BLL trends in Butte children ages 1–5 (n=2796) from 2003 to 2010 as compared to a reference dataset matched for similar demographic characteristics over the same period. Demographic factors incorporated into the analyses include child age, year and season of sample, house age, socioeconomic status, and race/ethnicity.

2.1. Butte dataset

The Butte dataset originated from medical records maintained by the BSB Health Department of patients recruited for regular blood lead testing through the state's WIC program. The blood lead samples were analyzed at a licensed commercial blood lead testing laboratory with a successful record of proficiency testing. Records included both capillary blood samples and venous (whole blood) samples; however, to avoid potential bias from counting both capillary and confirmatory venous results as independent measures for a given individual, all venous records were excluded from the study dataset. The capillary samples were analyzed by graphite furnace atomic absorption spectrometry (GFAAS) with an instrument detection limit of 1.0 μg/dL.

The data were compiled from the BSB Health Department's existing hard-copy records in June 2012 after obtaining necessary confidentiality agreements. All data entry was subjected to confirmation against original records. The initial database was comprised of 7278 blood lead records from residents of all ages, including pregnant women, infants, and young children. The following records were excluded from the database: 670 records missing a birthdate, a gender, or a street address; 156 records of venous samples, excluded to avoid potential bias from counting both capillary and confirmatory venous results as independent measures for a given individual; 2782 records from individuals younger than one year or older than 5 years; 826 records for samples collected outside the study years (only 21 blood lead records were collected before 2002); and 48 records for samples collected from children who did not live in Butte-Silver Bow County. After exclusions, 2796 records remained for the analysis comparing BLL data to an external reference population. These records were for 1697 children (some children were tested repeatedly over multiple years) who were sampled between 2003 and 2010. The study years were limited to 2003 and 2010 to correspond to National Health and Nutrition Examination Survey (NHANES) sampling periods.

Of the 2796 records, 364 were reported below the detection limit of 1.0 μg/dL; a higher proportion of non-detected values were reported in the more recently collected data. Extrapolation was selected as the method for assigning values for non-detects after conducting a sensitivity analysis using other treatments, such as setting the value equal to the detection limit or half of the detection limit. The geometric mean blood lead levels for each study period using the different methods did not differ significantly. Values for non-detects were extrapolated/assigned from the Butte distribution of values from the same test year using the log-normal regression on order statistics function for non-detect imputation of U.S. Environmental Protection Agency's ProUCL software (Version 5.0, Atlanta, GA). Address information for individual records was used to assign a year the residence was built (i.e., for a house age variable) from Montana State property tax records.

Blood lead data were also internally compared between Butte neighborhoods. Neighborhoods in Butte were initially defined based on Butte's seven main census tracts; this afforded access to potentially representative demographic and socio-economic information not included in the blood lead database. Address information for each record was used to assign geographic coordinates to each property using ArcGIS 10.1 (ESRI, Inc.) and Google Maps. The coordinates for each property were plotted spatially against the census tract boundaries. The data were partitioned into eight neighborhoods (termed N1-N8); the first seven were defined by the boundaries of census tracts in the developed areas of Butte with a 500 meter buffer to include houses near, but not falling in, one of the seven tracts. The eighth neighborhood was defined by the boundaries of the town of Walkerville within the eighth census tract that surrounds the more developed areas (Fig. 1). After excluding 72 records from rural areas of the eighth census tract, 2724 blood lead records remained for the neighborhood comparison.

2.2. Dataset for reference population

The NHANES provides nationally representative data on blood lead samples collected from survey participants, ages one year and older, selected from the civilian non-institutionalized household population of the U.S. (Centers for Disease Control, 2013b). Although data from other state and regional blood lead monitoring programs were considered, NHANES data were selected due to the following factors: 1) availability of data for the same years and the same age range as the majority of the Butte data; 2) detection limits sufficiently low ($<$1 μg/dL) to analyze statistical trends in the data; 3) availability of sufficient demographic variables to adjust for other factors associated with higher BLLs; and 4) comparability of the sample size to the Butte dataset. Four sets of survey years were included in the analysis to overlap the majority of available Butte data: 2003–2004, 2005–2006, 2007–2008, and 2009–2010. From 2003 to 2010, the NHANES dataset included a total of 2937 blood lead records for children matching the study age range (12–60 months). The sample size for survey periods ranged from 676 in 2007–2008 to 806 in 2005–2006. All NHANES data were collected through venous collection methods with detection limits ranging from 0.25 to 0.28 μg/dL over the 4 surveys; only a single blood sample was below the detection limit.

2.2.1. Weighting factors

Weighting factors developed and applied to the NHANES dataset allowed for creation of a reference BLL dataset representative of the distribution of BLLs for Butte children that would be expected without the influence of Butte's mining history. The Centers for Disease Control and Prevention (CDC) uses population adjustments to make the NHANES data representative of the U.S. population (Centers for Disease Control, 2013b) because the survey may oversample populations of interest for a particular survey period. The CDC's adjustments provide a precedent for use of a weighting procedure to adjust the underlying NHANES data to reflect a subpopulation.

Differences between the NHANES and the Butte population in demographic factors associated with higher BLLs were considered for developing the weights: gender, age, season of the blood test, the year the child's residence was built (referred to as "house age"), poverty level, and race. Development of weights for child gender and age was straightforward due to the comparability of available information for each record in both the Butte and NHANES datasets. For some factors, available information was not directly comparable between the two datasets. For example, the date of the blood test was available in Butte, but the NHANES records only provided test season (i.e., May–October as summer/fall and November–April as winter/spring) within a two-year period. In this case, the Butte data were coded to fall into a season and two

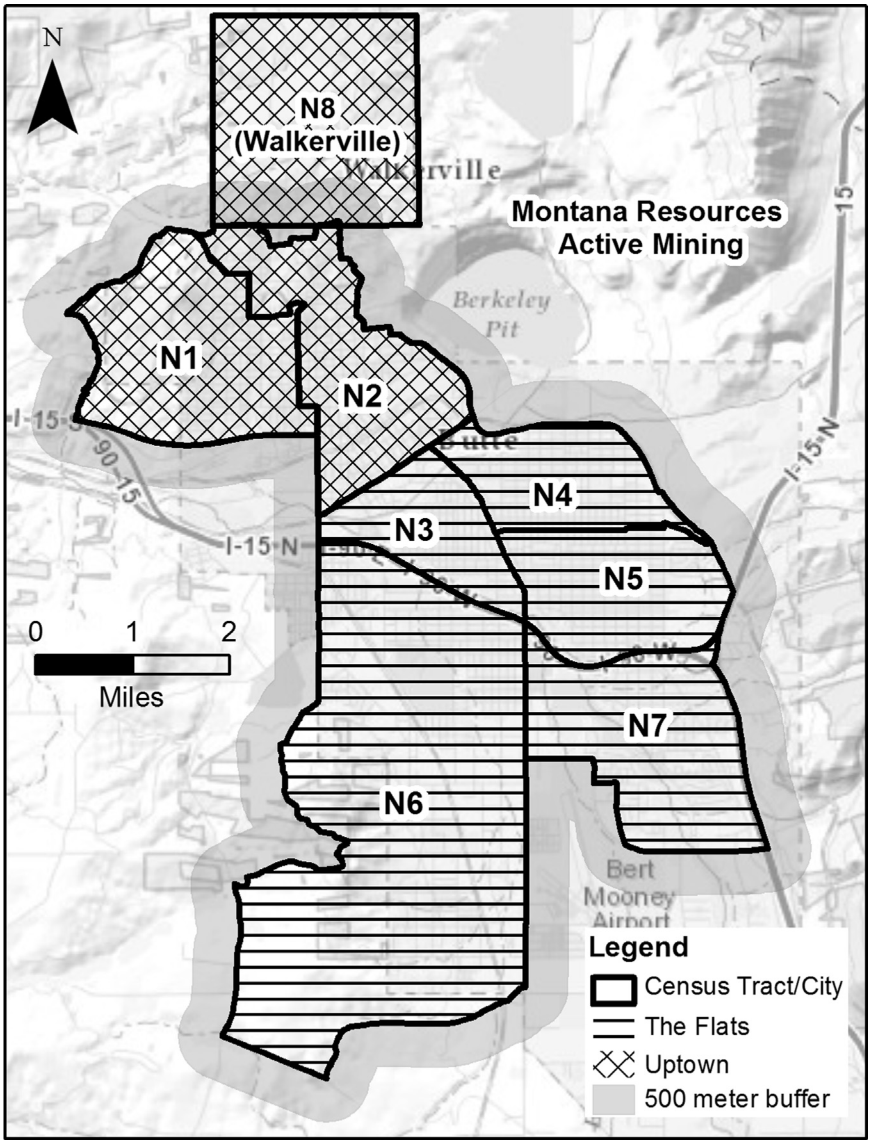

Fig. 1. Approximate boundaries of Uptown and the Flats. Census tract and city boundaries acquired from Montana Geographic Information Clearinghouse, Montana State Library.

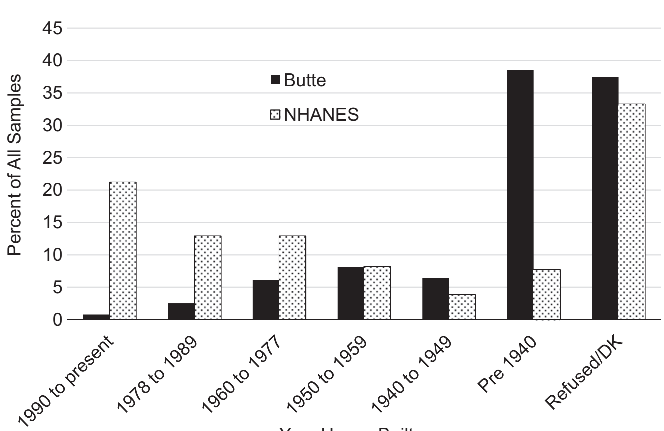

Fig. 2. House age comparison, survey period 2005–2006. The age of house (year built) in which children resided when tested during the 2005–2006 period illustrates the different distribution of this risk factor in the Butte dataset vs. the original NHANES dataset. DK – subject did not know the year home was built.

year period consistent with the NHANES categories.

As shown by the Centers for Disease Control (2013a), geometric mean BLLs were 0.6–0.8 μg/dL higher during 2003–2006 for U.S. children living in houses built prior to 1950 compared with children living in houses built during or after 1950. The percentage of children with BLLs above 5 μg/dL was markedly higher for those living in houses built prior to 1950. During 2003-2006, 8.8 percent of children in houses built before 1950 had BLLs above 5 μg/dL compared with 1.4 percent of children in houses built on or after 1978. House age information for both datasets was categorized into six group: pre-1940, 1940–1949, 1950–1959, 1960–1977, post 1977, and "missing" when the information was not available. These categories were selected to account for declining use of lead in paint over time, as well as increased prevalence of deteriorated paint in older housing.

Children living in poverty have higher BLLs compared with children in wealthier households (Centers for Disease Control, 2014, 2013a; Jones et al., 2009). Two measures are used in national studies to assess poverty status: the poverty-to-income ratio (PIR) and Medicaid enrollment. The PIR is the total family income divided by the federal poverty level specific to family size, year, and state of residence, with low income households defined as having a PIR of less than 1.3. During the years 2003–2010, both low income measures were associated with higher geometric mean BLLs in U.S. children (0.4–0.6 μg/dL higher) (Centers for Disease Control, 2013a). The difference in the percentage of children with high BLLs (i.e., greater than 5 μg/dL) was even more marked.

Poverty level information for the Butte data was not requested at the time of sample collection. According to BSB and WIC staff most Butte blood lead records (90–95 percent) corresponded to children from WIC eligible families. In Montana, WIC eligibility corresponds to a PIR of 1.75 or less. A sensitivity analysis showed little difference when 90 percent or 95 percent of the Butte study population was assumed to be WIC eligible (PIR $\leq$ 1.75), so we assumed 95 percent. For NHANES records missing a PIR, another sensitivity analysis was performed to examine the change in geometric mean BLLs with assumptions that the missing values were greater than or less than 1.75, or after imputing the values from the known distribution of NHANES PIR values in ProUCL. Imputation was chosen as the appropriate method because it did not result in skewing the geometric mean BLLs from the NHANES dataset. Given the limited poverty information, the PIR categories were used only to weight the NHANES data, not as a variable in the regression models.

BLLs in non-Hispanic black children have long been observed to be higher than those in non-Hispanic white and Mexican children (Jones et al. 2009). This disparity has been reduced over time, but continues to be significant (Jones et al. 2009, Centers for Disease Control, 2013a), making this an important population characteristic to consider. From 2003–2010 average BLLs were higher in non-Hispanic black children in the U.S., and the percent of these children with BLLs greater than 5 μg/dL was more than twice as high as the percent of non-Hispanic white and Mexican children with elevated BLLs (Centers for Disease Control, 2013a).

Unlike the NHANES dataset, record-specific data on race for the Butte dataset was not available. Estimated data from the U.S. Counties Census for Butte-Silver Bow County (U.S. Census Bureau, 2010) were used instead. These census data indicate the racial composition of the Butte dataset was predominantly white, non-Hispanic. Further, a review of the full census data by tract indicated that the racial composition was substantially similar to the county-wide estimates.

2.2.2. *Selection of weights*

Weights were calculated as Butte to NHANES ratios based on the percentage of records from each dataset that fell into each variable category. For example, the percentage of records in the Butte age group 12–35 months in 2003-2004 was divided by the percentage of records in the same NHANES age group and study period. Weights greater than one signify a higher percentage of records in a given category in Butte than in NHANES. Weights calculated for child age, child gender, and test season showed that distributions were similar for the two datasets; ranging from 0.69 to 1.3 (see Supplemental Material, Table S2).

For house age, poverty, and child race, weights varied more widely between records in each category in the Butte dataset compared with NHANES (see Supplemental Material, Table S2 and S3). In the Butte dataset, there was a preponderance of houses built prior to 1940, whereas, for the NHANES dataset, the majority of houses were built since 1960 (Fig. 2). This resulted in weights ranging from 3.5 to 4.3 in the Pre-1940 category and weights from 0.076 to 0.21 in the Post 1977 category (Supplemental Material, Table S3). In both datasets, a similar proportion of records did not include house age (i.e., 33–36 percent). The weights were much lower for the high PIR category ($>$ 1.75) than for the low PIR

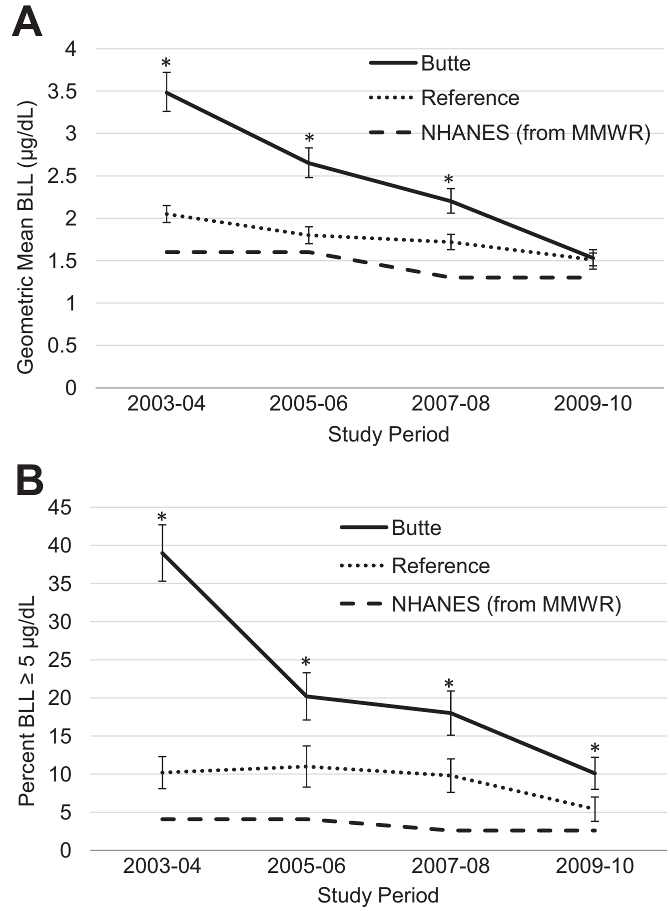

Fig. 3. Comparison of BLLs in Butte, reference dataset, and NHANES. Panel A compares geometric mean BLLs for the Butte dataset vs. the reference dataset over four testing periods (NHANES geometric mean only available every 4 years). Panel B compares the percentage of BLLs greater than or equal to 5 μg/dL in each dataset (NHANES percentage only available every 4 years). Error bars represent 95% confidence interval around the mean. *Statistically significant difference between Butte and the Reference population for a given study period.

category ($\leq$ 1.75) reflecting the predominance of WIC eligible children in the Butte dataset vs. the more representative income groups in the NHANES dataset. When categorized over all survey years, weights ranged from 1.3 to 1.8 for the low PIR category compared to 0.11–0.19 for the high PIR category (see Supplemental Material, Table S4). The NHANES blood lead dataset showed a much more diverse racial composition compared with Butte for time increments of 2003–2006 and 2007–2010 (Table 1). These differences resulted in high weights for white, non-Hispanic records in NHANES (ranging from 2.6 to 3.4) and very low weights for all other racial groups (as low as 0.0057 for the black, non-Hispanic group in 2003–2004; see Supplemental Material, Table S4). Based on these results, different weighted scenarios were tested, as described in Section 2.3.

2.3. *Statistical analysis*

All statistical analyses were executed in SAS Version 9.3 (SAS Institute Inc., Cary, NC). Because the blood lead data were log-normal, they were log-transformed prior to analysis. Child age was treated as a continuous variable in the models, while the other variables were treated as categorical: test year (two years per category), test season (i.e., summer/fall or winter/spring), child gender (male/female), house age (Pre 1940, 1940–1949, 1950–1959, 1960–1977, Post 1977, and missing). For the reference population comparison, source (Butte or reference) was an additional

Table 1
Racial/ethnic composition comparison.

Butte Silver Bow county race/ethnicity[a]	2003–06	2007–10
Non-Hispanic white	92.4%	91.9%
Non-Hispanic black	0.2%	0.3%
Hispanic or Latino origin	3.1%	3.5%
Other race-including multiracial	4.2%	4.4%
NHANES race/ethnicity	**2003–06**	**2007–10**
Non-Hispanic white	28%	28%
Non-Hispanic black	28%	18%
Mexican American	33%	26%
Other Hispanic	6%	10%
Other race - including multiracial	6%	6%

[a] Source: U.S. Counties Census estimates for 2003–2010.

variable. Neighborhood (N1–N8) was included as a variable in the neighborhood comparison. Descriptive statistics were generated for the Butte and NHANES datasets, including geometric mean BLLs and percentage of BLLs greater than 5 μg/dL and 10 μg/dL for each year (2003–2010).

Univariate analyses were performed to check each variable's significance with respect to BLL for the reference population and the Butte population. Linear mixed regression models were built for both the reference population comparison and the neighborhood comparison based on univariate results. The SAS Mixed procedure (SAS Institute, Inc., Cary, NC) was used to account for the repeated measures for some individuals. An autoregressive covariance structure was used so that measurements farther apart in time were assumed to be less correlated than observations closer in time. Significant interaction terms were used to stratify the full models. To determine whether the rate of decline in BLLs over time varies in the two comparisons, a Chi-squared test statistic using the coefficients and standard errors for test year (treated as a continuous variable) from each model was calculated and used to determine if the null hypothesis that the coefficients were the same could be rejected at a significance level of $\alpha=0.05$.

The reference comparison required a weighted regression. All Butte records had a weight equal to one in the model. Four different scenarios for weighting the NHANES data were tested in the regression model using standard weighting procedures in SAS. The first scenario applied weights based only on house age while the remaining three scenarios applied weights as the product of two or more individual variable weights as follows: house age and poverty; house age and race; and house age, poverty, and race. The full model was run four times to examine the effects of the four weighting scenarios. The scenario which combined the weights for house age, poverty, and race was chosen because the combination of the three variable weights did not appear to significantly skew the NHANES data in one particular direction (see Supplemental Material, Figure S1). To distinguish it from the original NHANES data, the weighted dataset is referred to as the reference dataset in the results. Residual plots were generated to assess the fit of the models.

3. Results

General summary statistics for the Butte dataset are provided in Table 2. Geometric mean BLLs for 2010 (1.55 μg/dL) were less than half of the levels for 2003 (3.49 μg/dL). The percentage of BLLs above 10 μg/dL declined by a similar magnitude, decreasing from 3.4 percent to 1.5 percent. The percentage of BLLs above 5 μg/dL declined by an even greater margin, decreasing from 33.6 percent in 2003 to 9.5 percent in 2010.

3.1. Reference population comparison

Univariate analysis from the Butte population showed statistically significant differences in BLLs for child age, child gender, year house built, test year, and test season (see Supplemental Material, Table S5). For the NHANES data, consistent with previous analyses (Centers for Disease Control, 2013a; Jones et al., 2009), statistically significant differences in the reference BLLs were seen for child age, year house built, test year, and test season, but not for gender (see Supplemental Material, Table S6). All variables were included in the fully adjusted model. The interaction term for test year and source was significant ($p<0.0001$); therefore, the final model was stratified by source (Butte or reference).

For the final stratified model, the association between each independent variable (i.e., test year, house age, child age, child gender, or test season) and BLL is presented after adjusting for all the other variables (Table 3). Table 3 shows *p*-values for three different models 1) comparing Butte categorical data to the Butte reference category; 2) comparing reference population categorical data to the reference population reference category, and 3) comparing the Butte categorical data to reference population categorical data.

For 2003–2004, 2005–2006, and 2007–2008, geometric mean BLLs were higher for Butte than for the reference dataset (Fig. 3A). By 2009–2010, adjusting for all other variables, the geometric mean BLL for Butte was no longer significantly higher (1.53 μg/dL in Butte compared with 1.51 μg/dL for the reference dataset, $p=0.89$; Fig. 3A). Based on the results of the Chi-squared test, the Butte geometric mean BLLs declined by 24 percent per 2-year increment from 2003 to 2010, while the reference dataset BLLs showed a significantly slower decline of 9 percent per 2-year increment ($p<0.0001$). Over the full study period, the percentage of high BLLs in Butte declined dramatically, whereas the percentage of high BLLs (>5 μg/dL) for the reference data was mostly stable (Fig. 3B). Across all testing periods, including 2009–2010 where the geometric mean BLLs were not significantly different, the proportion of high BLLs in Butte was greater than in the reference dataset. Residual plots of the reference and Butte data from the final stratified model indicated a good fit of the data to the model (see Supplemental Material, Figure S2).

3.2. Neighborhood comparison

In order to define neighborhood areas within Butte, a Tukey's Multiple Comparison was performed. This analysis showed statistically similar distributions of BLLs for two groupings of geographically similar neighborhoods (see Supplemental Material, Table S1). N1, N2, and N8 are located at higher elevations, include

Table 2
Butte blood lead summary statistics.

Year	*n*	GM (μg/dL)	GSD (μg/dL)	95th percentile (μg/dL)	Percent ≥5 μg/dL	Percent ≥10 μg/dL
2003	351	3.49	2.01	9.10	33.6	3.4
2004	319	4.36	1.76	9.51	44.8	4.4
2005	312	3.35	1.83	8.60	24.7	2.6
2006	326	2.63	1.93	7.03	16.0	1.8
2007	342	2.44	2.16	7.90	16.1	2.0
2008	324	2.55	2.15	9.15	20.1	4.0
2009	361	2.01	2.10	6.80	10.8	1.4
2010	461	1.55	2.42	6.60	9.5	1.5

n – Sample size; GM – geometric mean; GSD – geometric standard deviation.

Table 3
Final model results stratified by Butte vs. Reference.

Variable and category		Butte *n*	GM (μg/dL) (95% CI)	*p* Value	Reference population[a] *n*	GM (μg/dL) (95% CI)	*p* Value	Comparison *p* Value
Child test age (estimate)[b]		2796	0.97 (0.94, 0.99)	0.0040*	2937	0.92 (0.90, 0.94)	< 0.0001*	0.0006#
Child gender	Male[c]	1355	2.51 (2.38, 2.64)	–	1427	1.72 (1.65, 1.79)	–	< 0.0001
	Female	1441	2.22 (2.11, 2.34)	< 0.0001*	1510	1.80 (1.73. 1.87)	0.056	< 0.0001
Year house built	Missing	991	2.5 (2.38, 2.62)	< 0.0001*	1023	1.65 (1.59, 1.72)	< 0.0001*	< 0.0001
	Post 1977	111	1.84 (1.60, 2.11)	< 0.0001*	868	1.45 (1.30, 1.61)	< 0.0001*	0.011
	1960 to 1977	153	2.25 (2.00, 2.54)	< 0.0001*	397	1.63 (1.48, 1.79)	< 0.0001*	< 0.0001
	1950 to 1959	158	2.36 (2.09, 2.67)	< 0.0021*	244	1.67 (1.53, 1.83)	< 0.0001*	< 0.0001
	1940 to 1949	244	2.45 (2.23, 2.69)	< 0.0016*	113	1.84 (1.70, 1.98)	< 0.0001*	< 0.0001
	Pre1940 [c]	1139	2.9 (2.77, 3.04)	–	292	2.47 (2.37, 2.57)	–	< 0.0001
Test year	2003–2004	670	3.48 (3.26, 3.72)	< 0.0001*	753	2.05 (1.95, 2.15)	< 0.0001*	< 0.0001
	2005–2006	638	2.65 (2.48, 2.83)	< 0.0001*	806	1.80 (1.70, 1.90)	< 0.0001*	< 0.0001
	2007–2008	666	2.2 (2.06, 2.35)	< 0.0001*	676	1.72 (1.63, 1.81)	< 0.0001*	< 0.0001
	2009–2010[c]	822	1.53 (1.44, 1.63)	–	702	1.51 (1.44, 1.59)	–	0.89
Test season	Winter/spring	1414	2.13 (2.03, 2.24)	< 0.0001*	1389	1.56 (1.48, 1.66)	< 0.0001*	< 0.0001
	Summer/fall[c]	1382	2.62 (2.49, 2.75)	–	1548	1.98 (1.91, 2.06)	–	< 0.0001

n – Sample size; GM – geometric mean; CI – confidence interval.

* Statistically significant ($p < 0.05$) compared with the reference category.

\# Statistically significant ($p < 0.05$) comparison between Butte and Reference Population.

[a] Based on weighting for house age, poverty, and race.

[b] Child age was treated as a continuous variable and model result is an estimate (unitless) instead of a geometric mean.

[c] Reference category used for comparison with all other categories for a given variable.

the historical (more than 150 year old) city center located atop former mine workings, and correspond to the area referred to by Butte residents as "Uptown." The N3–N7 group (designated "the Flats") corresponds to an area at lower elevation that is farther from past and present mining operations and includes a larger proportion of newer residential and commercial areas compared with Uptown.

All variables examined in the univariate analysis were significant and were retained for inclusion in the fully adjusted model. Results of the fully adjusted model stratified by Uptown and the Flats showed that, in both areas, the children tested in 2009–2010 had lower geometric mean BLLs than the children tested in earlier years ($p < 0.0001$; Table 4; Fig. 4a).

Geometric mean BLLs in Uptown were slightly higher compared with the Flats in each period, and were significantly higher only in 2007–2008 and 2009–2010 ($p = 0.001$ and 0.02, respectively).

Based on the results of the Chi-squared test, the rate of BLL decline from 2003 through 2010 is not statistically different for Uptown and the Flats ($p = 0.07$). In Uptown, BLLs have declined at a rate of 11 percent per two-year period compared to a decline rate of 14 percent in the Flats (Table 4; Fig. 4a). Additionally, the percentage of BLLs greater than or equal to 5 μg/dL declined comparably between Uptown and the Flats over the study periods, with the percentage statistically significantly lower in the Flats in each of the two-year periods (Fig. 4b).

In both neighborhoods, BLLs were higher when tested in summer/fall than in winter/spring (summer/fall BLLs were 27 percent higher than winter/spring BLLs in Uptown and 18 percent higher in the Flats) (Table 4). BLLs were higher in Uptown than in the Flats during both test seasons, but the differences were statistically significant only during the summer/fall when the Uptown geometric mean was 2.91 μg/dL vs. 2.42 μg/dL in the Flats.

Table 4
Results from stratified linear mixed model with *p* values comparing Uptown to the Flats.

Variable	Variable categories	Uptown *n*	GM (μg/dL) (95% CI)	*p* Value	The Flats *n*	GM (μg/dL) (95% CI)	*p* Value	Comparison *p* Value
Child test age (estimate)[a]		732	0.96 (0.93, 0.99)	1.0	863	1.00 (0.96, 1.04)	0.007*	0.03#
Child gender	Male [b]	539	2.76 (2.51, 3.04)	–	777	2.34 (2.18, 2.50)	–	0.01
	Female	663	2.43 (2.19, 2.69)	0.006*	745	2.14 (2.00, 2.30)	0.03*	0.06
Year house built	Missing	350	3.20 (2.95, 3.47)	1.0	595	2.17 (2.04, 2.30)	< 0.0001*	< 0.0001
	Post 1977	19	1.70 (1.20, 2.41)	0.0007*	77	1.86 (1.58, 2.20)	0.0002*	0.5
	1960-1977	24	2.52 (1.88, 3.37)	0.1	128	2.20 (1.93, 2.51)	0.02*	0.4
	1950-59	42	2.73 (2.14, 3.48)	0.2	116	2.18 (1.90, 2.51)	0.02*	0.09
	1940-49	196	2.50 (2.24, 2.80)	0.0002*	48	2.45 (1.99, 3.03)	0.5	1.0
	Pre 1940 [b]	571	3.20 (3.00, 3.42)	–	558	2.63 (2.47, 2.81)	–	< 0.0001
Test year	2003–2004	295	3.57 (3.17, 4.02)	< 0.0001*	356	3.45 (3.17, 3.77)	< 0.0001*	0.7
	2005–2006	253	2.84 (2.52, 3.20)	< 0.0001*	369	2.52 (2.32, 2.74)	< 0.0001*	0.1
	2007–2008	300	2.58 (2.30, 2.89)	< 0.0001*	356	1.99 (1.83, 2.17)	< 0.0001*	0.001
	2009–2010 [b]	354	1.72 (1.54, 1.92)	–	441	1.44 (1.34, 1.56)	–	0.02
Test season	Winter/spring	568	2.30 (2.09, 2.54)	< 0.0001*	801	2.07 (1.94, 2.21)	< 0.0001*	0.09
	Summer/fall [b]	634	2.91 (2.64, 3.21)	–	721	2.42 (2.26, 2.59)	–	0.004

n – Sample size; GM – geometric mean; CI – confidence interval.

* Statistically significant ($p < 0.05$) compared to reference category.

\# Statistically significant ($p < 0.05$) comparison between Uptown and the Flats.

[a] Child age was treated as a continuous variable and model result is an estimate (unitless) instead of a geometric mean.

[b] Reference category used for comparison with all other categories for a given variable.

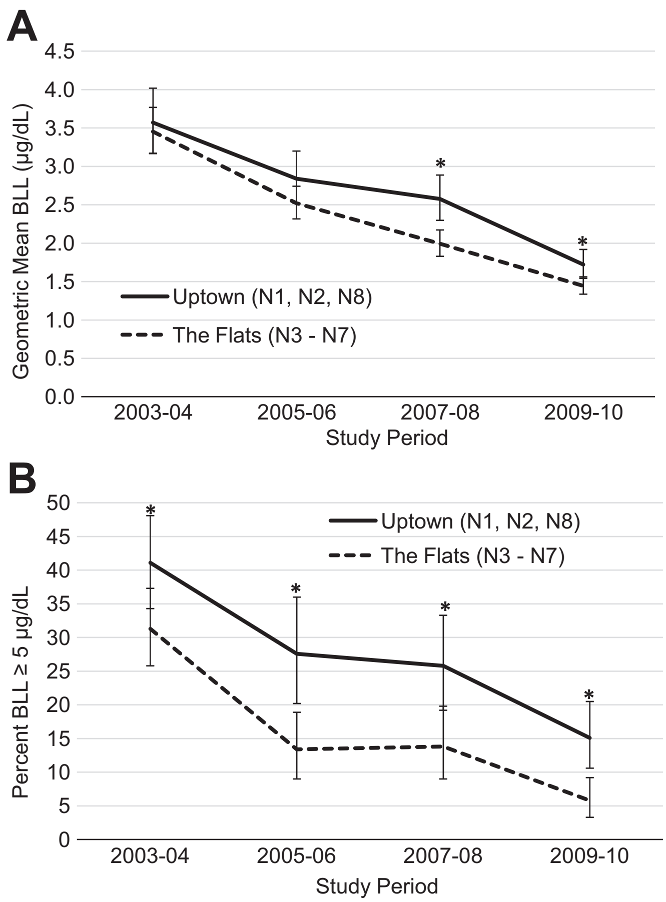

Fig. 4. Comparison of BLLs in Uptown and the Flats. Panel A compares geometric mean BLLs for each two year study period between Uptown (N1, N2, and N8) and the Flats (N3–N7). Panel B compares the percentage of records greater than or equal to 5 µg/dL in each neighborhood. Error bars represent 95% confidence intervals around the mean. *Statistically significant difference between Uptown and the Flats for a given study period.

When the house age categories were compared across Uptown and the Flats (Table 4), BLLs were higher in Uptown children for all house age categories, except the post-1977 house age group. However, the neighborhood differences were statistically significant only for children from properties built before 1940 and the missing house age category.

4. Discussion

The BLLs among children tested in the BSB Health Department program declined rapidly from 2003 through 2010. A more rapid decline in average BLLs was seen in Butte than in the reference population, which could possibly reflect the ongoing community-wide remediation activities that mitigate exposure to lead sources. Through 2010, 498 abatements had been conducted in Uptown (288 for soil and 210 for paint), compared with 47 abatements (6 for soil and 41 for paint) in the Flats. No renovations have been necessary for plumbing in either neighborhood. Though studies have demonstrated the effectiveness of lead hazard control interventions within homes, few have documented effectiveness at decreasing BLLs at concentrations less than 10 µg/dL (Clark et al., 2011). Remediation of contaminated soil has also been reported to contribute to reductions in house dust lead concentrations and BLLs (Sheldrake and Stifelman, 2003), with effectiveness increasing as larger neighborhood areas were completed. The present study suggests that the community-wide remediation measures, residential measures, and screening efforts may have been effective in lowering BLLs.

Despite this progress, the percentage of high BLLs in this Butte population has not yet reached the reference population level, suggesting that a small percentage of children are still experiencing higher than expected lead exposure. Based on the results of the neighborhood comparison, a greater portion of BLLs that exceed 5 µg/dL are found in children in Uptown. Uptown is closer than the Flats to areas of historical and ongoing mining and naturally-occurring mineralized zones (Weed and Emmons, 1897). Outdoor lead exposure may contribute more to BLLs for residents of Uptown based on our finding that the higher BLLs in Uptown were statistically significant only for children tested during the summer and fall. Children spend a higher proportion of time outdoors during these warmer seasons and have more opportunities to contact soil (Zahran et al., 2013). Transport of soil and outdoor dust containing lead to indoors is also increased during warmer periods when surface soils are more likely to be exposed (snow is not present) and can be more easily blown in or tracked into homes (Haley and Talbot, 2004; Laidlaw et al., 2005). A recent study of BLLs in Detroit area children found late summer BLLs averaged between 11 percent and 14 percent higher than BLLs measured in January (Zahran et al., 2013). Summer/fall BLLs were even more elevated in Butte (18–27 percent higher that winter/spring BLLs), likely reflecting factors such as the arid climate in Butte and the availability of outdoor recreational activities for children.

One potentially confounding factor that may explain the residual risk of BLLs that exceed 5 µg/dL for children residing in Uptown is that more participants in Uptown than the Flats were found to reside in the oldest housing in Butte. Within the pre-1940 house age category, the majority of the Uptown homes were built before 1910, while most of the oldest houses in the Flats were built after 1910. Additionally, though owner/renter status was not available for the Butte dataset, the 2010 census data shows that 72 percent of residents in the census tracts associated with the Flats own their own home compared to 49 percent for Uptown. Living in a renter-occupied home has been associated with higher BLLs (Lanphear et al., 2003), as these homes may not have the same level of upkeep as owner-occupied homes, possibly contributing to increased lead exposure.

The final model showed children from the “missing house age” category residing in Uptown had higher BLLs than children from the “missing house age” category residing in the Flats. Examination of known house age data for both areas reveals a more even distribution of house ages for children tested from the Flats relative to children tested from Uptown, where a disproportionate number of children resided in homes built around 1900. Assuming the distributions of house ages for the “missing” category for both Uptown and the Flats match the respective distributions for the known data, the proportion of children tested who resided in the oldest Butte homes would be even greater in Uptown than reported in the existing known house age data.

Based on the findings of Sheldrake and Stifelman (2003), children's BLLs are affected by neighborhood as well as individual yard soil lead concentrations, which may explain why some individual children still have higher exposure even when average exposure has declined in Butte. These findings support the value of a community-wide cleanup approach.

This study demonstrates the importance of considering potentially confounding demographic factors associated with higher BLLs prior to evaluating the contribution of suspected lead exposure sources to observed BLLs. In Butte, a comparison of observed BLLs to a BLL distribution representative of the U.S. as a whole would provide little insight into the contribution of local exposure sources to higher BLLs.

The extent to which these demographic factors may be associated with BLLs for the Butte dataset can be examined by comparing the NHANES reference data weighted according to Butte demographic and socioeconomic characteristics to the NHANES data that are the basis for the current CDC blood lead reference value of 5 μg/dL (representing the 97.5th percentile nationally from 2005 through 2008). In contrast, for the NHANES reference dataset weighted according to Butte demographic and socioeconomic factors, 10.3 percent of BLLs exceed 5 μg/dL during the same time period (Fig. 3B). This comparison shows that variation in a community's distribution of demographic factors associated with higher BLLs such as poverty, house age, and race has a substantial impact on the percentage of BLLs over 5 μg/dL. Having adjusted for variation of three key demographic and socioeconomic factors associated with high BLLs in the current study enables us to derive insights regarding other factors not accounted for in the model that may contribute to BLLs, such as local lead exposure sources, analytical method differences, or other demographic factors.

4.1. Limitations

The available data had several limitations. In the present study, both NHANES and Butte blood lead data were collected as part of other programs, and individual information on factors commonly associated with higher blood lead levels was not always consistently available. Individual data on race/ethnicity and poverty were included in the NHANES database, but were not collected in Butte. These variables had to be inferred from census data and first-hand details from the BSB Health Department. House age was included in the NHANES database, but with a large proportion classified as "missing". The Butte blood lead records did not include house age, but this information was obtained for a majority of records by geo-referencing addresses with property tax records; the remaining records in the Butte dataset were also classified as "missing". Butte records included the specific sample date, whereas the NHANES records only included a two year sample period and winter/spring vs. summer/fall. Data on other factors that are associated with variation in BLLs were not available in the Butte dataset, notably data on maternal education and own/rent status of housing.

Different blood collection methods were used in the two programs: NHANES using venous blood draws vs. Butte using blood collected onto filter paper from capillary samples. Despite initial concern that this difference might have overestimated Butte blood lead values due to external contamination (ACCLP, 2012), this concern was not believed to be a significant limitation because Butte WIC sample collection methods included preparation of the skin location using laboratory-provided wipes that are designed to reduce the potential for external lead contamination. With a paired test design, correlation coefficients between capillary and venous methods have been reported to range from 0.96–0.98 (Schlenker et al., 1994). The laboratory used for the Butte blood lead data reports: "The correlation between paired, simultaneously drawn extraction method filter paper and venous samples is >0.970. Additionally, undetected-elevated and, falsely-elevated rates may be considered clinically insignificant. These findings are documented by three published, peer-reviewed studies involving 363 paired, simultaneously drawn extraction method filter paper and venous sample comparisons" (Srivuthana et al., 1996; Yee and Holtrop, 1997; Yee et al., 1995).

Due to differences in the available data, weighting could not fully account for differences between the distributions of values for the Butte and reference datasets. Butte income status was inferred based on WIC eligibility and treated as a binary variable. While there is a high level of confidence in the binary variable, WIC eligibility may reflect a wide range of income levels over which lead risks might vary. Both the Butte and reference datasets included a substantial proportion of BLLs with unknown house age for which the actual distribution likely differs between the two datasets.

Information on specific lead exposure sources was generally not available for either dataset, for example lead concentrations in drinking water, soil and house dust lead data were not available for the full study period. We did not have information for Butte blood lead data on the timing of soil remediation or lead abatements of individual Butte properties relative to sample dates for children living at those properties. Similarly, the NHANES dataset did not include data on lead paint abatement. Without lead exposure data, we are not able to identify specific causes of blood lead concentration changes over time or of differences between Butte and the reference dataset. For both Butte and NHANES datasets, previous residence is not available, and for Butte, there is no history of time at current residence. Low income children at highest risk for elevated BLLs are likely to move frequently.

4.2. Conclusions

Given Butte's significant history of mining-related lead sources and the extensive activities taken over several decades to reduce exposures to such sources, Butte BLL declines likely reflect the cumulative effectiveness of screening efforts, community-wide remediation, and the ongoing metals abatement program in Butte in addition to other factors not accounted for by this study. As evidenced in Butte, abatement programs that include home evaluations and assistance in addressing multiple sources of lead exposure can be an important complement to community-wide soil remediation activities.

While the Butte multi-pathway program is likely responsible for the steeper decline in Butte BLLs compared to a reference dataset, persistent disparities across Butte suggest continuation of these efforts is warranted. This study found that demographic factors associated with higher BLLs are important to consider when characterizing community lead risks, and presents an approach for consideration of such factors in the context of a historical mining community. The results highlight the importance of multiple approaches for reducing lead exposure.

Our analysis may be relevant when assessing the association between identified lead sources and BLLs in other communities. For the U.S., similar methods could be used to create an external reference population weighted according to community-specific demographic factors using NHANES data. In order for such an approach to be successful, it is important that adjustments for demographic factors be representative of the population for whom blood lead data are available or collected. Random selection of study participants may simplify demographic adjustments by enabling reliance on census data. In our study, the population tested was not representative of the general population demographics, and additional effort was required to obtain representative demographic information. This approach is not limited to lead and could be applied to other biomarkers of chemical exposure, medical conditions, or health indicators included in NHANES for which key demographic factors may vary greatly by community.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2015.12.028.

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